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Doped iron garnet materials for magnetic photonic crystals

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Abstract – We have established a set of technologies for the deposition and annealing of magneto-optic garnets for use in photonic crystals. Devices for sensing magnetic fields and polarisation control using reconfigurable photonic crystals are being developed.

Introduction

Magnetic photonic crystals (MPC) are expected to provide great improvements and novel functionalities (such as fast tunability) in optical integrated circuits for optical communication networks and sensors. Until now, since the first report about the superior magneto-optical properties of bismuth-substituted iron garnet [1], this material remains being considered the best magneto-optical material for use in MPC structures. This is because it demonstrates the highest Faraday rotation in the visible and near infrared spectral regions and excellent optical transmittance in the infrared region. At the same time, the practical use of MPC in real photonic devices is seriously limited now due to high excess optical absorption levels observed in sputtered magneto-optical films, especially in the visible spectral region. As a result, until now the Faraday rotation angles of only up to 7.5° (observed only at the saturated magnetisation, in a material without remanence) were demonstrated experimentally in MPC structures with a “defect mode” in the MPC’s photonic bandgap engineered for the near-infrared spectral region [2]. Based on the analysis of existing literature-reported data, special investigations are necessary for improving the situation in the area of magneto-optical materials suitable for use in MPC structures, and the main question in such investigations is the ability to recognize the source of the additional optical absorption in the RF-sputtered films in comparison with mono-crystalline epitaxial films. The second question arises: what is the optimal composition of the garnet film for creating the layers within MPC structures suitable for practical development of photonic devices? To successfully fabricate MPC structures, a number of material properties must be optimized simultaneously, including the optical absorption, specific Faraday rotation, surface quality, and either the presence or absence of the domain structure and magnetic memory (remnant magnetisation).

MO FILMS FABRICATION, CHARACTERISATION AND OPTIMISATION OF A NANOSTRUCTURED MAGNETIC FIELD SENSOR

We have manufactured and characterised several batches of high-quality iron garnet films of thicknesses between 50 and 5000 nm, doped with Dy and Ga ions, which possessed a sufficient level of uniaxial magnetic anisotropy for orienting the film’s magnetic moment in a direction perpendicular to the film plane. This ensured a nearly-square magnetic hysteresis loop of our films, thus enabling excellent magnetic memory properties. The deposition technology used was RF magnetron sputtering using a composite oxide-mix-based target of nominal stoichiometry $\text{Bi}_2\text{Dy}_1\text{Fe}_4\text{Ga}_1\text{O}_{12}$. In order to crystallise the amorphous sputtered films into polycrystalline ferrimagnetic garnet phase whilst preserving the high layer quality, a post-deposition high-temperature oven annealing process had to be developed and optimised. Magnetic photonic crystals using iron garnet layers as magnetic constituents are therefore unique in the sense that not only it is the structural periodicity but also the presence of crystalline-phase layers is what makes these structures belong to the class of photonic crystals. We characterised the films optically, magnetically and magneto-optically and found that the layers possessed a combination of properties which is highly desirable for the design and manufacture of integrated-optics devices based on MPC (the results are shown and explained in Fig. 1). In particular, the magneto-optic quality of our material, determined by the specific Faraday rotation and optical absorption, is in some wavelength regions comparable to the best reported garnets with much higher Bi content per formula unit, which however do not possess the magnetic memory properties desirable in many applications.

We designed an optimized MPC-based reflection-mode magnetic field sensor/visualizer structure using our MPC optimization algorithm and software reported in [3]. The properties of garnet layers achieved using our deposition and annealing technologies are also suitable for the design and manufacture of other integrated-optics devices proposed in [3]. Shown in Fig. 2 is a typical configuration of a reflection-mode magnetic field visualizer or sensor using a thick iron garnet film as a sensing element, which we propose to replace with an optimised MPC, the properties and structure of which are shown in Fig. 3. Our analysis shows that significant improvements in both the sensitivity and spatial resolution of this type of sensing devices are expected, as well as very large Faraday rotation angles at the design wavelength. Such Faraday rotations are expected to be the largest in all reported MPC structures.

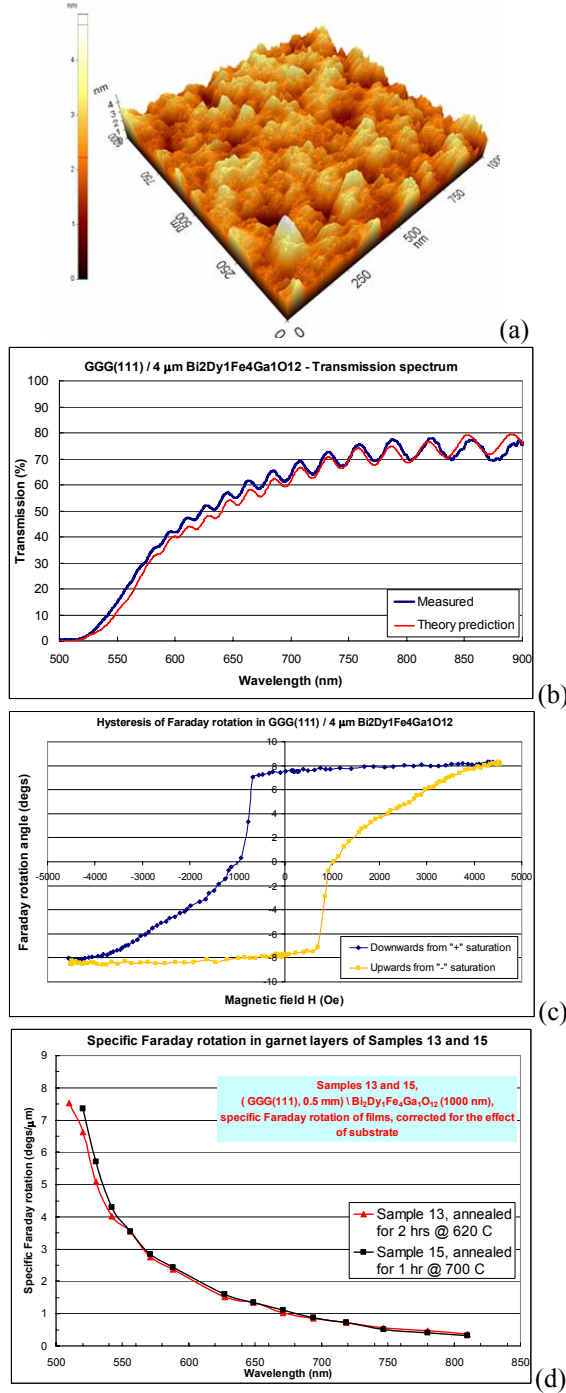


Fig.1. (a) Results of surface quality inspection (AFM), and (b-d) the optical, magnetic and MO characterisation of a 4 μm thick garnet-phase layer of Bi₂Dy₁Fe₄Ga₁O₁₂ showing a measured hysteresis loop of Faraday rotation at 633 nm and good magnetic memory properties achieved through selecting the garnet composition that provides a sufficient level of uniaxial magnetic anisotropy. RMS surface roughness of our garnet layers is typically about 2 nm across a randomly-selected film area of 1 μm². The combination of optical, magnetic and MO properties achieved in our garnet layers makes them very attractive for use in nanostructured photonic devices and sensors.

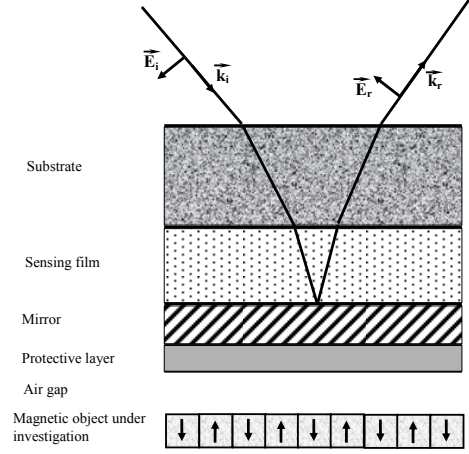


Fig.2. Operation of MO thin film sensors in reflection mode.

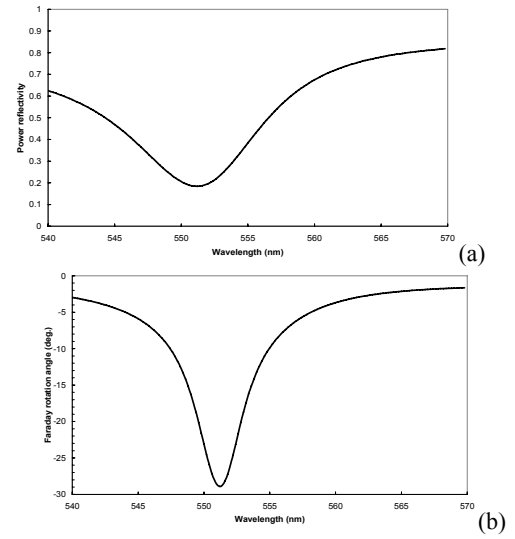


Fig.3. Spectra of reflectivity (a) and Faraday rotation in reflection mode (b) of an optimized 1.53-μm thick magnetic field sensor structure based on $\lambda/4$ stack GGG/(M)1(LM)4(M)2(ML)6/Ag, where M = (Bi,Dy):IG, L = GGG, designed for the operation in the visible wavelength region using the material characterisation data shown.

Conclusions

We have manufactured layers of doped iron garnet material with very high optical and magneto-optical quality, which are suitable as components of future magnetic photonic crystals possessing novel functionalities that are attractive for integrated-optics devices.

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